SUSY after 1/fb

(with some prejudice)

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Outline

- Theoretical intro: SUSY & the weak scale (MSSM & beyond)
- Looking at the current status (circa SUSY11)
- A (partial) list of other things that can be looked for from now on (besides keep pushing current limits up)

  (light 3rd gen', weak inos, displaced objects, low MET scenarios, long decay chains/compressed spectra, ...)
- Conclusions

SUSY & the weak scale

- SUSY provides a nice framework for stabilizing the ElectroWeak scale

$$\frac{m^2_{Higgs}}{2} = -\boxed{|\mu|^2} + \ldots + \boxed{\delta m^2_H}$$

$$\delta m^2_H \simeq -\frac{3y_t^2}{8\pi^2}\left(m^2_{Q_3} + m^2_{U_3} + |A_t|^2\right) \ln\left(\frac{M}{m_{\tilde{t}}}\right)$$

- (some of the) superpartners have to be light enough

  ($\mu \to$ higgsinos, m_{Q3},m_{U3},A_t $\to$ stop (sbottom))

- <u>more general</u> than the MSSM: 4-dim N=1 SUSY for Higgs+3rd generation (e.g no SUSY-extra dim'), perturbative Electroweak Sym' Breaking (e.g no SUSY-Technicolor, ...), ...)

- amount of cancelation has not been <u>directly</u> probed yet!

- What are the minimal requirements for a "natural" weak-scale SUSY?

  - 2 light stops
    - 1 light “left-handed” sbottom (required to be near the stops by weak isospin)
  - light higgsinos, i.e. 2 neutralinos and 1 chargino
  - a not-too-heavy gluino:

$$\delta m_{\tilde{t}}^2 \simeq \frac{8\alpha_s}{3\pi} M_3^2 \ln\left(\frac{\Lambda_M}{m_{\tilde{t}}}\right)$$

Gluinos correct the stop mass at 1-loop...
...and feed into the Higgs mass at two loops...

What about numbers?

hard to make sharp quantitative statements: what is “natural”?

10-9=1? 100-99=1? 1000-999=1? 1 part in 10^4? ...

$$m_{\tilde{t}}^2 \lesssim \frac{(700\text{GeV})^2}{1+A_t^2/2m_{\tilde{t}}^2}\left(\frac{3}{\ln\left(\Lambda_M/m_{\tilde{t}}\right)}\right)\left(\frac{M_{higgs}}{200\text{GeV}}\right)^2\left(\frac{20\%}{\Delta^{-1}}\right)$$

(e.g. Kitano & Nomura 2006)

Less problems w/ low scale mediation

bound ameliorated if something beyond the MSSM increase the Higgs mass (e.g. NMSSM, ...)

MSSM, large M_{Higgs}: $m_{\tilde{t}}^2 \lesssim (500\text{GeV})^2\left(\frac{3}{\ln\left(\Lambda_M/m_{\tilde{t}}\right)}\right)\left(\frac{20\%}{\Delta^{-1}}\right)$

Gluinos: $M_3 \lesssim 1.5\text{TeV}\left(\frac{3}{\log\left(\Lambda_M/m_{\tilde{t}}\right)}\right)$

Higgsinos: $|\mu| \lesssim 300GeV$

Digression: the MSSM

- The weak scale is determined by:

$$\frac{m^2_{Higgs}}{2} = -|\mu|^2 + \ldots + \delta m_H^2$$

$$\delta m_H^2 \simeq -\frac{3y_t^2}{8\pi^2}\left(m^2_{Q_3} + m^2_{U_3} + |A_t|^2\right) \ln\left(\frac{M}{m_{\tilde{t}}}\right)$$

- The physical Higgs mass is

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta + \frac{3}{4\pi^2}\frac{m_t^4}{v^2}\left[\log\frac{m^2_{\tilde{t}}}{m_t^2} + \frac{X_t^2}{m^2_{\tilde{t}}}\left(1 - \frac{X_t^2}{12 m^2_{\tilde{t}}}\right)\right] \qquad X_t = A_t - \mu \cot\beta$$

- LEP bound $m_H > 114$ GeV requires heavy stops

- tuning of ~ few %

Higgs & SUSY

- MSSM: minimal Higgs potential (like the SM Higgs for non-SUSY theories)
- minimality not necessarily followed by Nature (remember SU(3)xSU(2)xU(1), with 3 generations, ...)
- If more complicated Higgs sector:
  - constraints on SUSY particles from Higgs searches can go away
  - are direct SUSY searches affected?

general look on SUSY?

Flow of the talk

- if e.g. extended Higgs sector: more particles (generally charginos and neutralinos). Often similar signatures and topologies but with different σ and BR's (e.g. BR($\chi' \rightarrow Z\,\chi$) vs. BR($\chi' \rightarrow h\,\chi$))

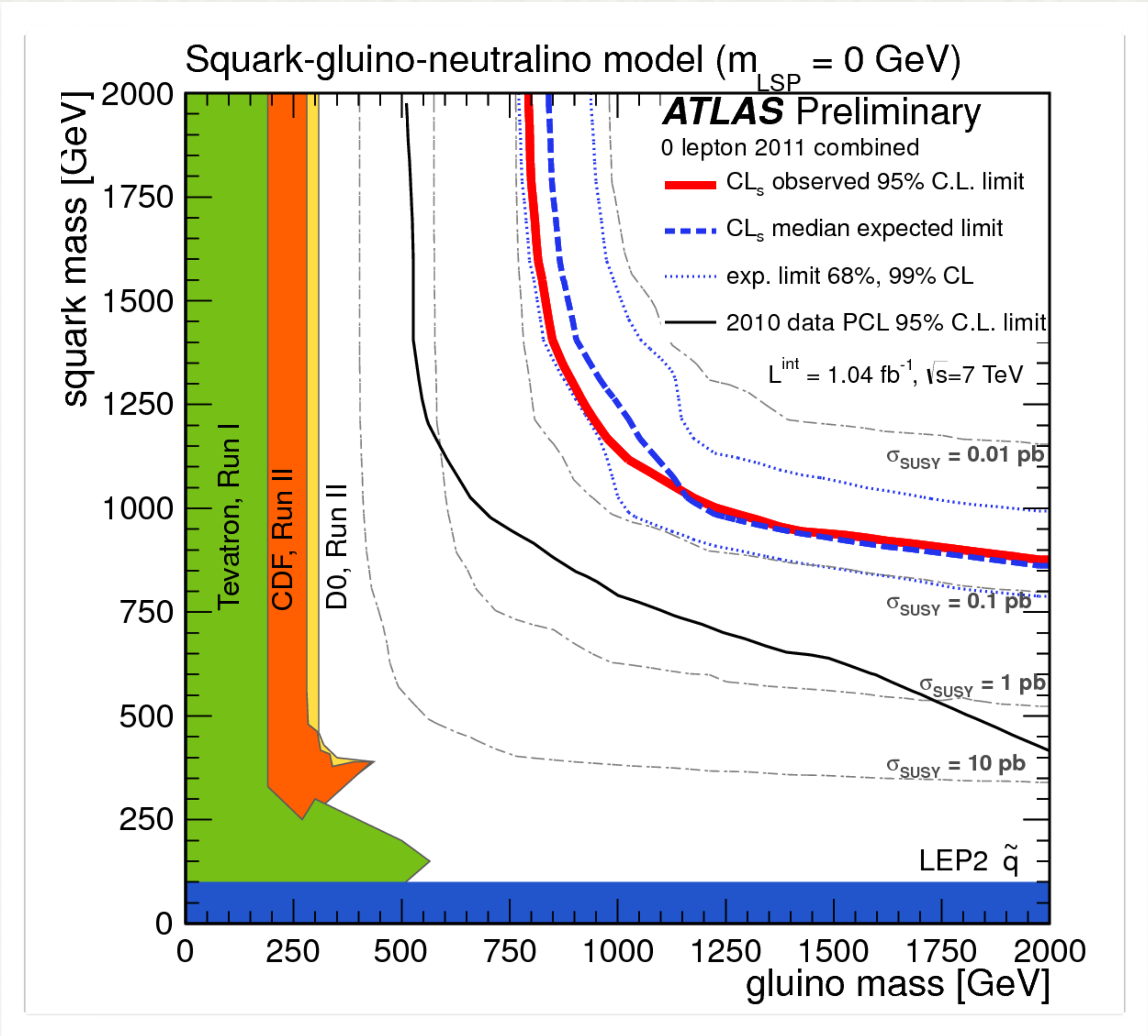
    - stick with MSSM spectrum but without committing to specific mass/BR's relations (MSSM has already enough variety). Kinematics is the guide

- Sometimes totally different pheno: keep an open eye on qualitatively very different signatures that can be obtained by adding very little on top of the MSSM (theory input for possible examples)

MSSM-like
R-parity conserving signatures

SUSY Searches

- By now we have learned that the 1st & 2nd generation squarks likely to be heavy (modulo pathologies)



- bounds > 800-1000 GeV from jets+MET searches with $1fb^{-1}$
- gluino limits above ~700 GeV from various other channels
- difficult to bring down light squarks considerably

1st-2nd gen' bounds vs. naturalness

- If SUSY breaking is flavor blind (soft masses $\propto 1_{3x3}$ in generation space @ mediation scale Λ_M)
    - no problem with flavor physics bounds (~ Minimal Flavor Viol') ☺
    - strong bound on light squark masses translates into bound on stop masses ☹
- even at low Λ_M~10TeV:

$$m_{\tilde{t}} \simeq m_{\tilde{q}} \gtrsim 700\mathrm{GeV} \quad \text{vs.} \quad m_{\tilde{t}} \lesssim (500 \div 700)\mathrm{GeV}$$

Splitting the 3rd gen' by Renormalization Group evolution doesn't help:

$$\delta m_H^2 \simeq 3\left(m_{Q_3}^2 - m_{Q_{1,2}}^2\right) \simeq \frac{3}{2}\left(m_{U_3}^2 - m_{U_{1,2}}^2\right)$$

1-loop, LL, not too large tanβ

Finetuning

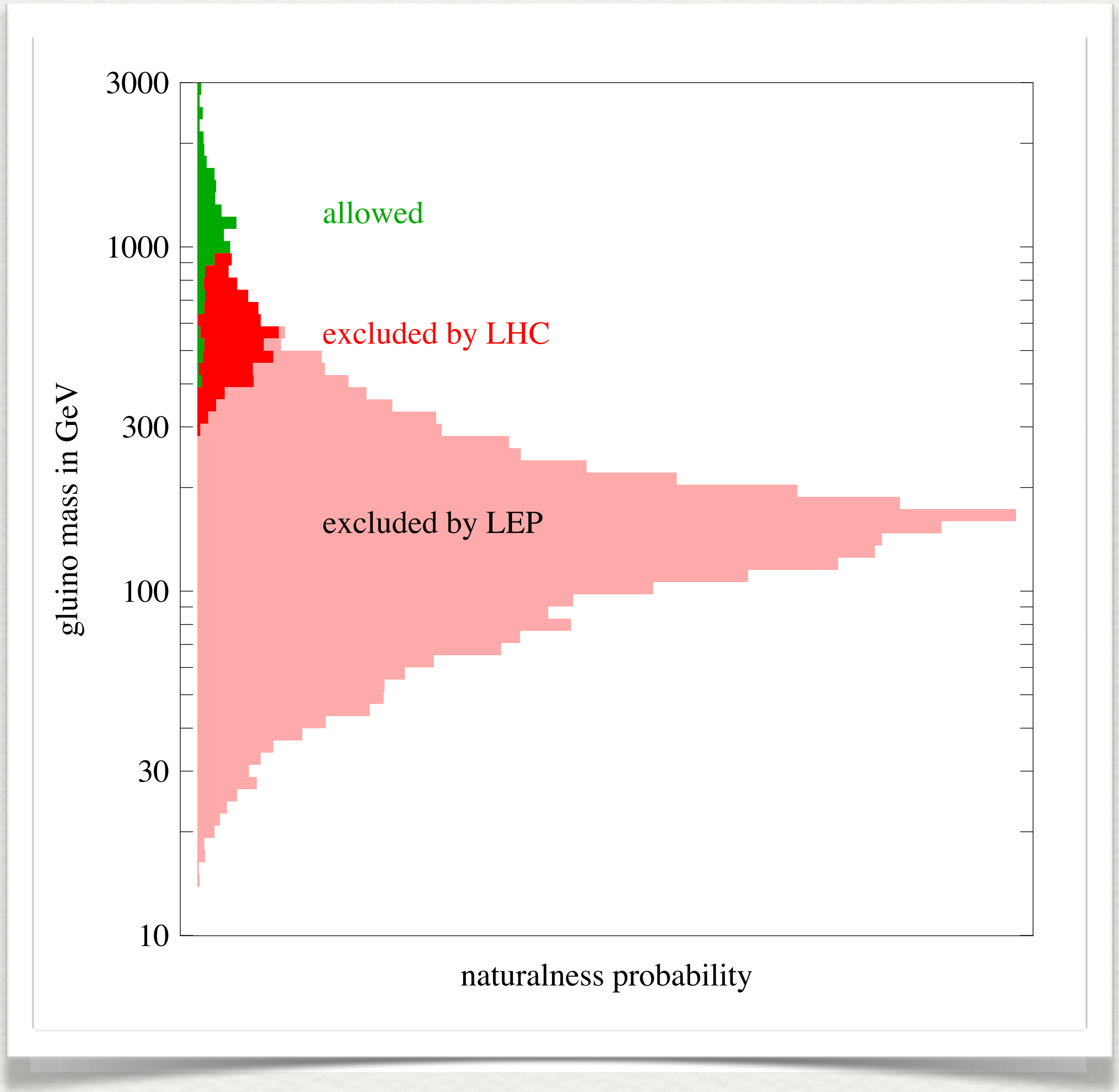
Splitting

(for conventional "natural" SUSY squarks better to be split from the beginning)

A certain tension starts building up irrespective of the LEP Higgs bound...

with high scale mediation models situation is much worse (log enhancement)

e.g. in the CMSSM, after 35 pb^{-1}:

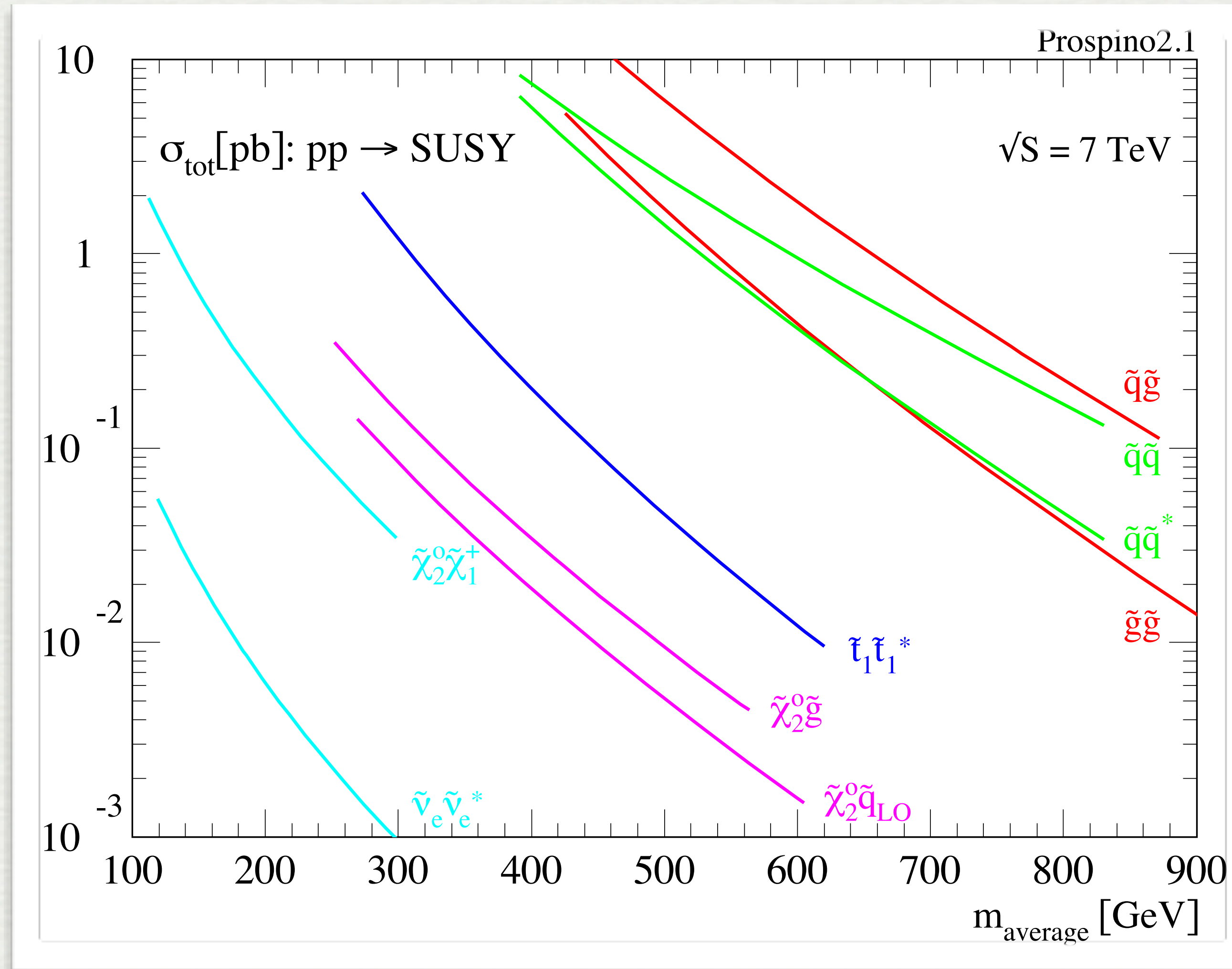


Strumia 2011

CAVEAT: all this story about naturalness may be misguidance (maybe anthropics, maybe just unlucky, ...). LHC will tell...

What about the rest?

- 1fb^{-1} is transition luminosity:
- $\mathscr{L}$<1fb^{-1} forced to look only for cascades initiated by gluinos/first two generation squarks
- $\mathscr{L}$>1fb^{-1} direct production of stops, sbottoms and EW inos starts to be progressively accessible



(For “natural SUSY” one can still have the options to wait for higher energy and keep pushing gluino limits, but naturalness may be just a theoretical bias...)

Light stops and sbottoms

(Dimopoulos & Giudice '95, Barbieri & Hall '95, Cohen et al. '96,
Gherghetta et al. '03,'11, Sundrum '09,
Barbieri et al. '09-'11, Craig et al. '11, ...)

- main ingredient for natural for Electroweak Symmetry Breaking (together with light higgsinos and not-too-heavy (<1-1.5TeV) gluinos)

- Splitting the squarks:

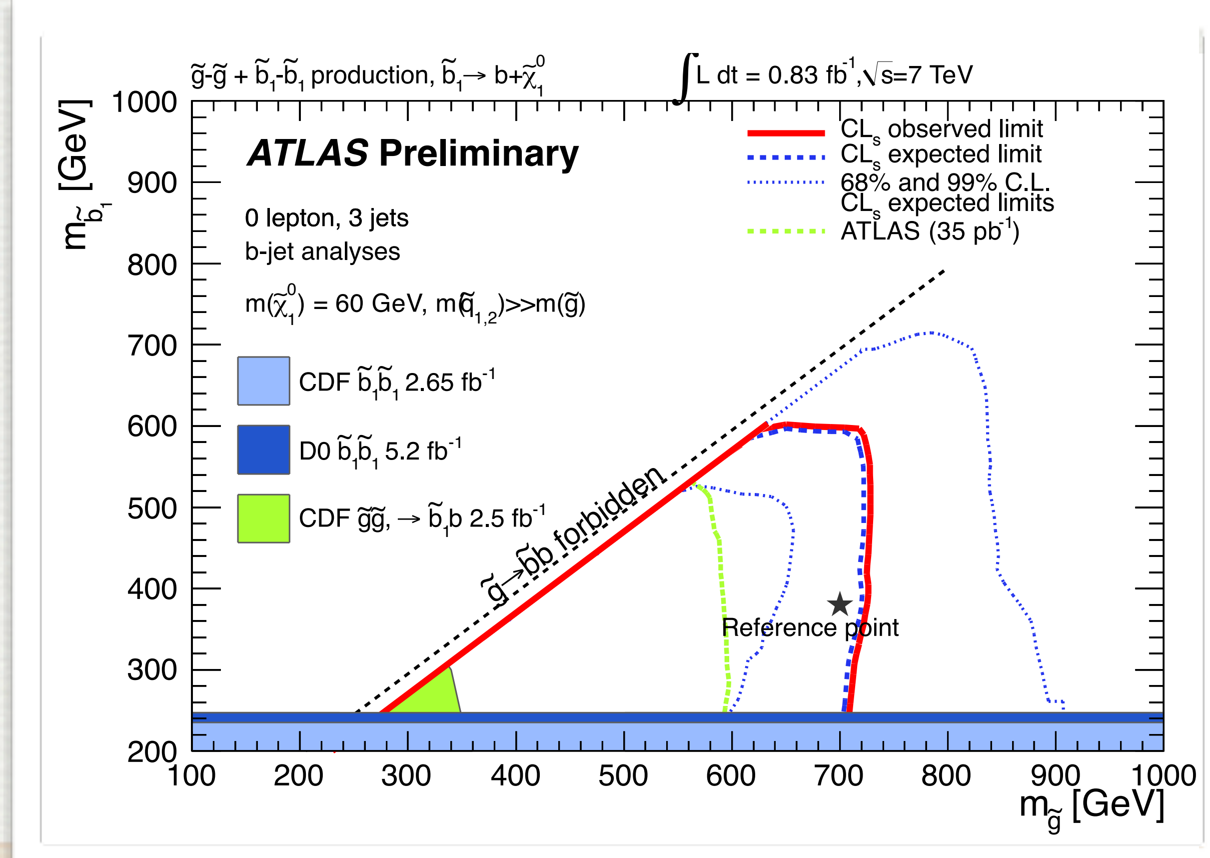
  - 3rd generation "light" vs. 1st-2nd generations "heavy" (originally motivated by flavor, now by LHC searches)

- Can be compatible with flavor constraints

Stops and sbottoms before the summer

- TeVatron:
  - Stops can still be light (even 120-180 GeV) (promptly decaying)
  - Sbottoms should be > 250 GeV (promptly decaying)
  - Additional small “holes” near kinematic degeneracies

LHC pre-fb^{-1}: exclusion driven by gluinos



3rd gen spectrum:

Two Stops: $$\begin{pmatrix} m_{Q_3}^2 + (180GeV)^2 & m_t(A_t - \mu\cot\beta) \\ m_t(A_t - \mu\cot\beta) & m_{U_3}^2 + (170GeV)^2 \end{pmatrix}$$

One Sbottom: $$m_{Q_3}^2 + (50GeV)^2$$

Fixed by Isospin

The other sbottom mass is basically free

Stops and sbottoms after the summer

(w/ J.Ruderman, N.Toro, A.Weiler, 1110.xxxx)

- Closer look to the analyses appeared this summer (ATLAS & CMS) to assess their implication for natural SUSY scenarios

	ATLAS			CMS		
	channel	$\mathcal{L}$ [fb^{-1}]	ref.	channel	$\mathcal{L}$ [fb^{-1}]	ref.
jets + $\not{E}_T$	2-4 jets	1.04	[1]	α_T	1.1	[9, 10]
	6-8 jets	1.34	[2]	H_T, $\not{H}_T$	1.1	[11]
b-jets + $\not{E}_T$	$b + 0l$	0.83	[3]	m_{T2} $(+b)$	1.1	[12]
	$b + 1l$	1.03	[4]			
multilepton + $\not{E}_T$	$1l$	1.04	[5]	$1l$	1.1	[13]
	$\mu^\pm\mu^\pm$	1.6	[6]	SS dilepton	0.98	[14]
	$t\bar{t} \to 2l$	1.04	[7]	OS dilepton	0.98	[15]
	$t\bar{t} \to 1l$	1.04	[8]	$Z \to l^\pm l^\mp$	0.98	[16]

+t',b' from CMS (PAS-EXO 36,50,51), 4lept from ATLAS (CONF-NOTE-144)

Stops and sbottoms after the summer

- 3rd gen direct production already constrained in the most favorable cases

e.g.:

$\tilde{t}_1, \tilde{t}_2$ 350 GeV

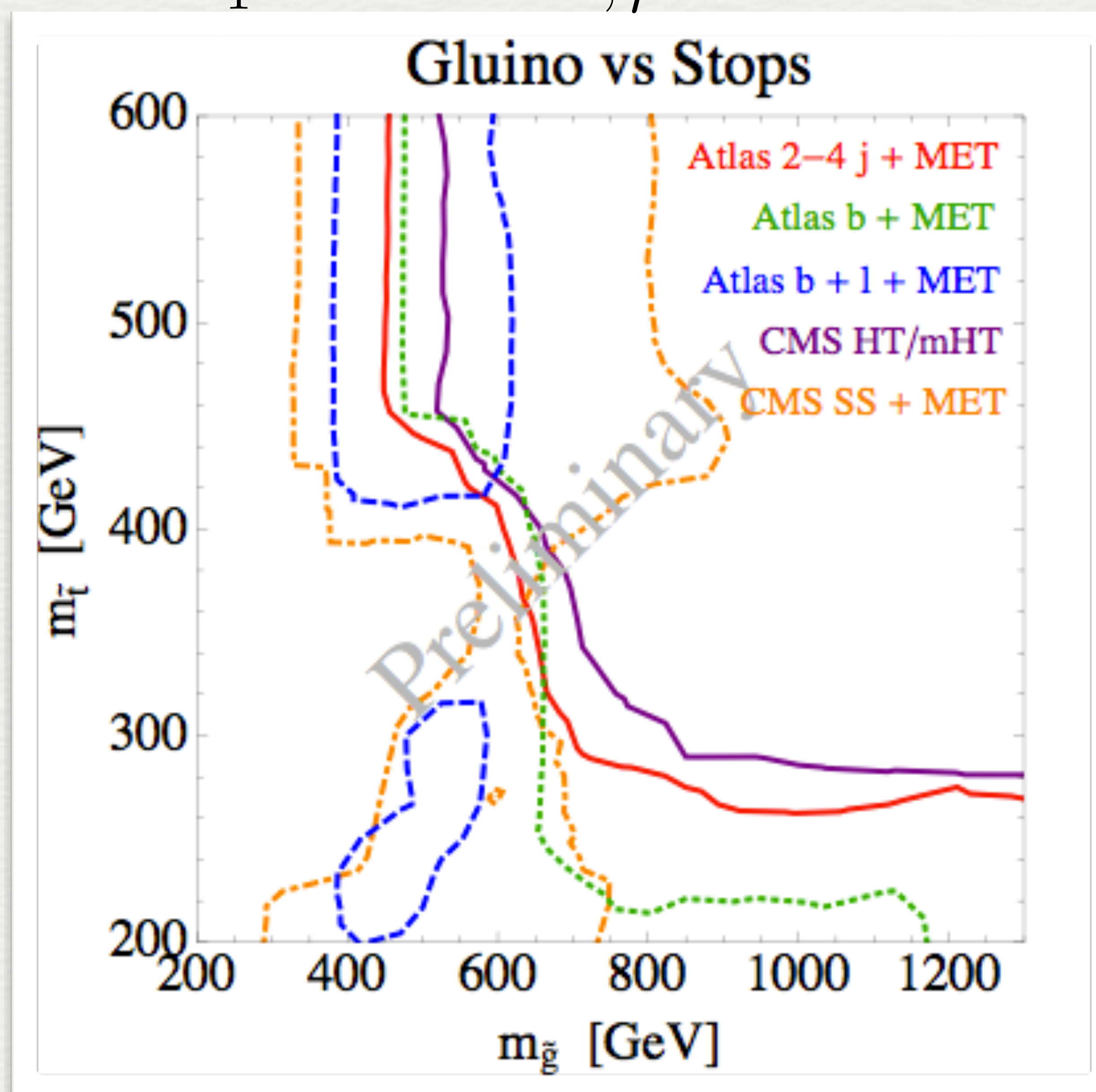
$\tilde{b}_1$ 300 GeV

$\chi^0, \chi^\pm$ 200 GeV

χ^0 100 GeV

"Teorists estimates":
wouldn't trust by more than
O(50GeV), but many times we get
much better agreement than that...

$M_1 = 100\,\mathrm{GeV}, \mu = 200\,\mathrm{GeV}$



Stops and sbottoms after the summer

Most of the power gained by having 3 states close to each other

(e.g. of total eff CMS j+MET: 50% from 2 stops, 50% from 1 sbottom)

Gain is still quickly lost by splitting:

via A_t: $\tilde{t}_2$, $\tilde{b}_1$, $\tilde{t}_1$

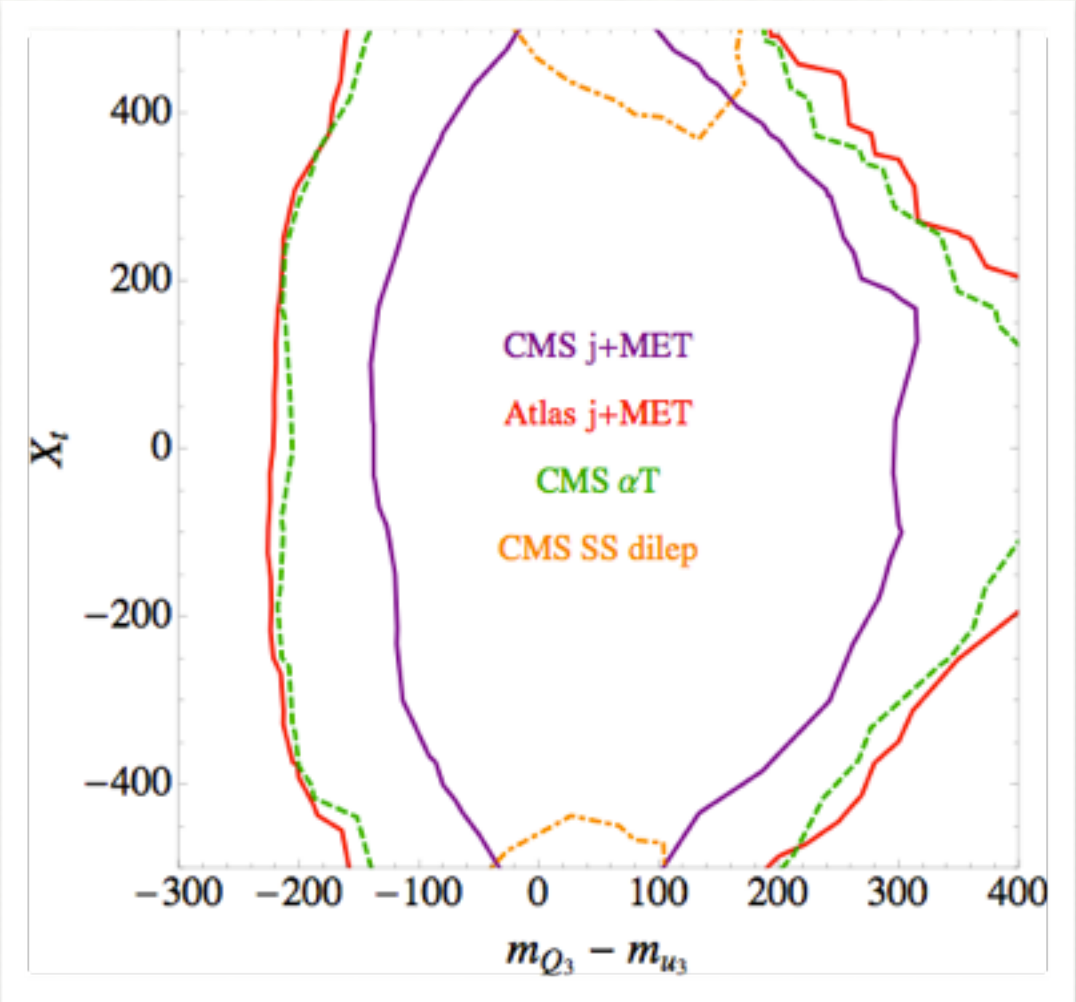
via m_{U3}-m_{Q3}: $\tilde{t}_2$, $\tilde{b}_1$ $\tilde{t}_1$ or $\tilde{t}_2$ $\tilde{b}_1$, $\tilde{t}_1$

most constrained (+Tevatron sbottoms bounds)

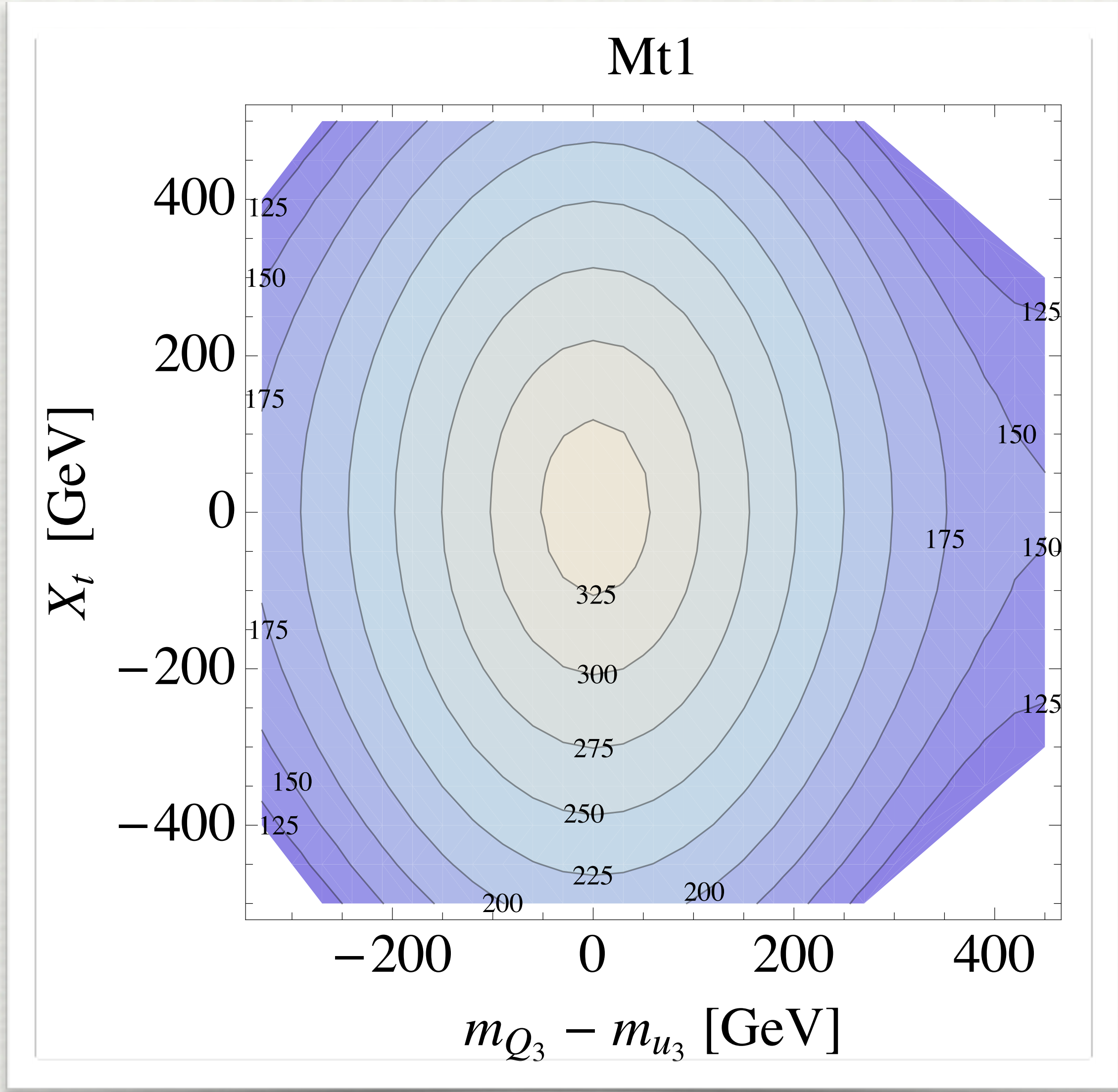
Stops and sbottoms after the summer

$$m_{Q_3}^2 + m_{U_3}^2 = 2 \cdot (450\,\mathrm{GeV})^2, M_1 = 100\,\mathrm{GeV}, \mu = 200\,\mathrm{GeV}$$

Finetuning changes



Finetuning is const

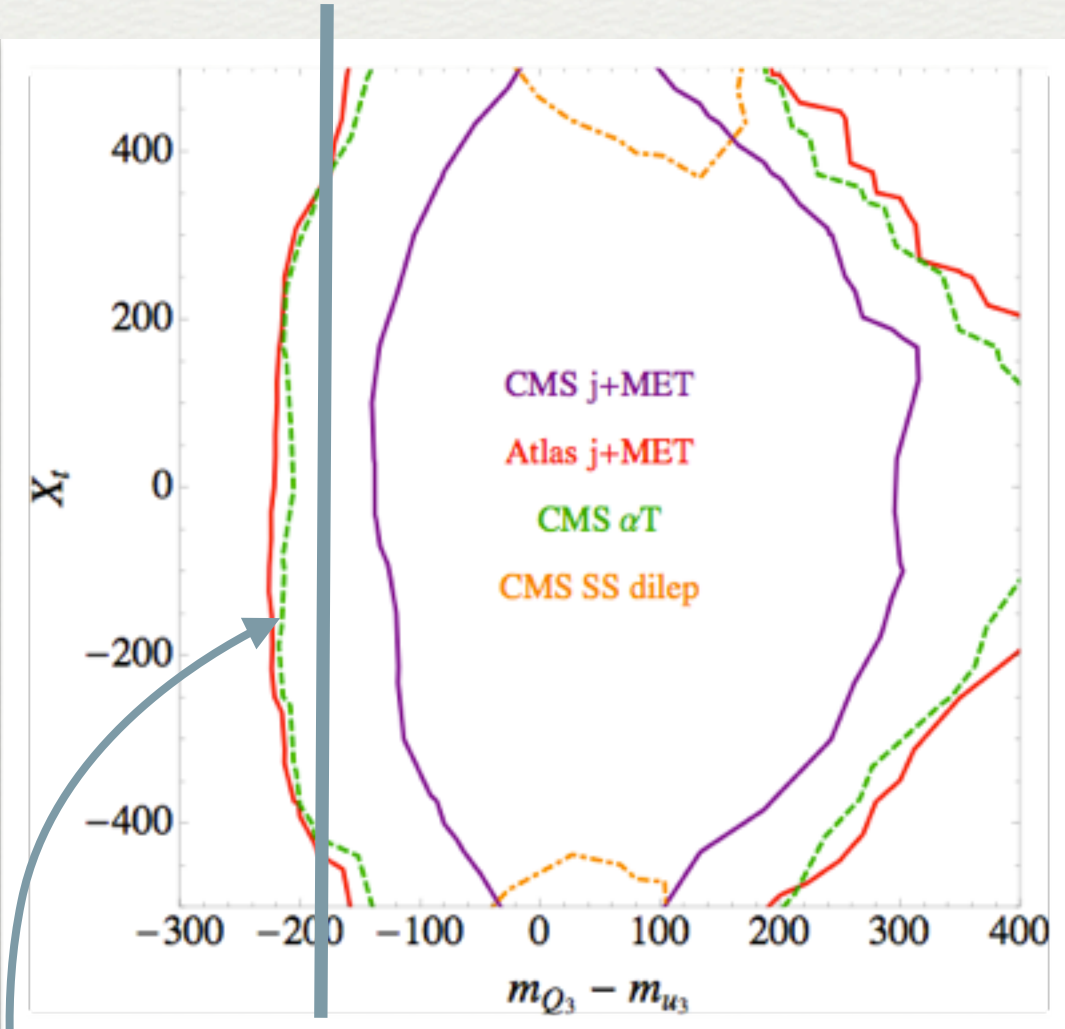


Lightest stop mass

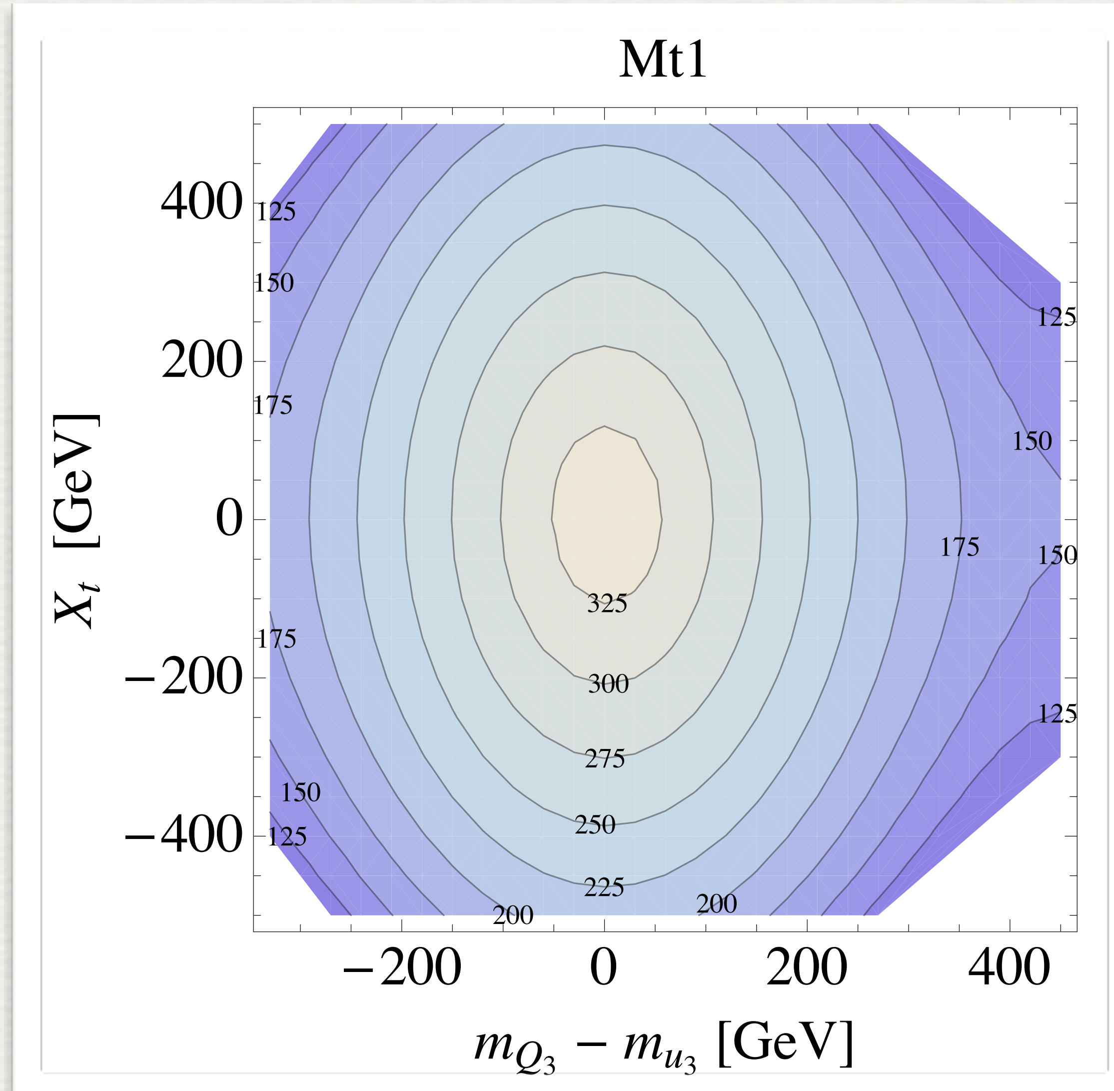
Stops and sbottoms after the summer

$$m_{Q_3}^2 + m_{U_3}^2 = 2 \cdot (450\,\mathrm{GeV})^2, M_1 = 100\,\mathrm{GeV}, \mu = 200\,\mathrm{GeV}$$

Finetuning changes



Finetuning is const

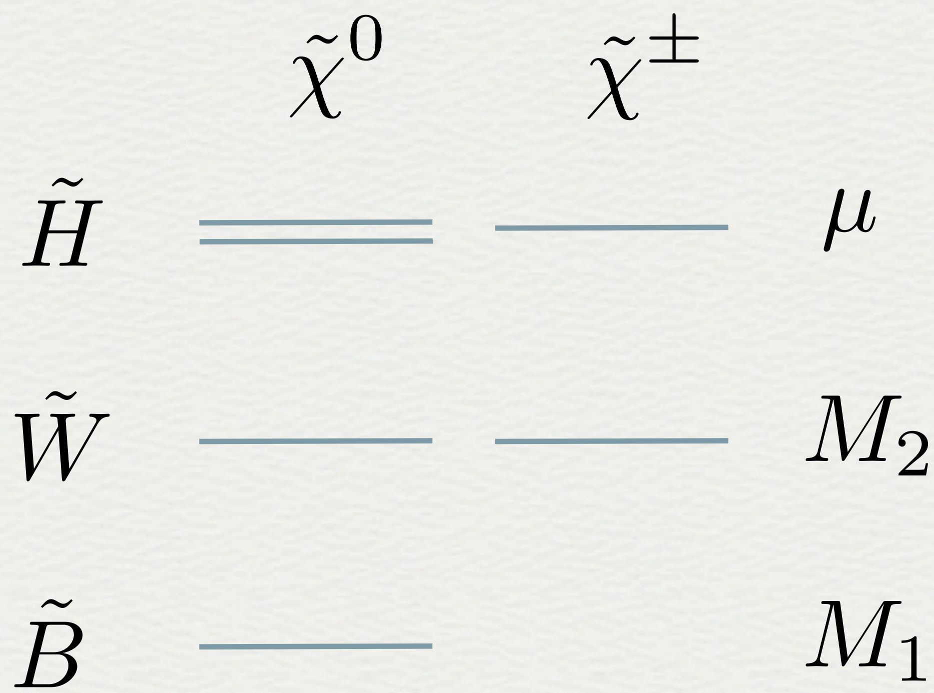


Lightest stop mass

Tevatron sbottom limits

Direct EW inos prod'

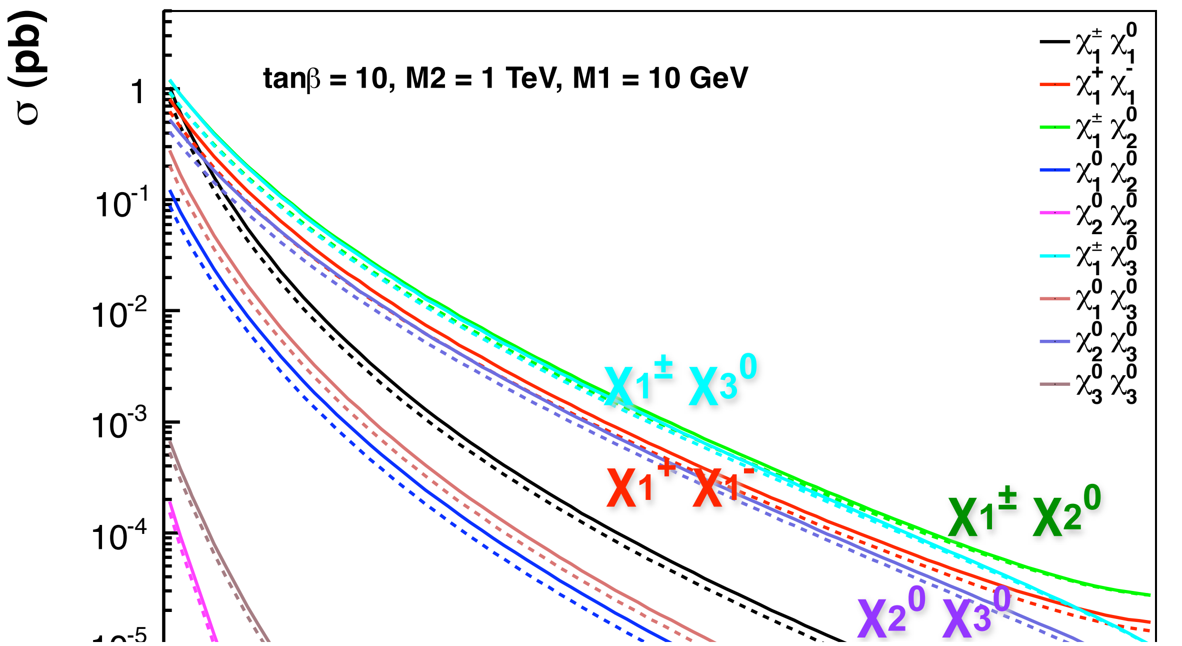
- In the MSSM 3 params control everything: M1, M2, μ



If 1 mass somewhat larger than the others, system simple enough to be tackled model independently...

If no sleptons around then decays involve gauge bosons and higgs(es). Changing ordering of masses changes only BR's and σ.

(+ "Simplif' model" for the case with 1 on-shell slepton already presented in 2008 by S.Thomas & Rutgers CDF group) light Higgsino $M_1 < \mu < M_2$

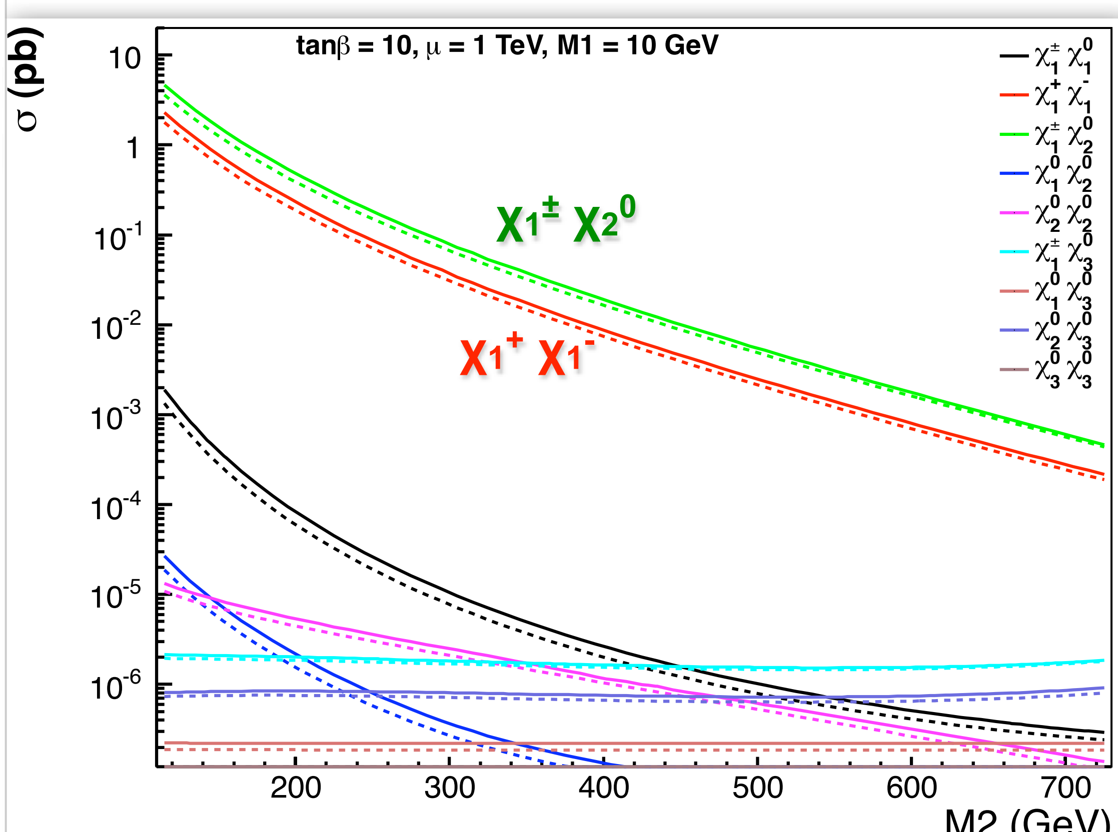


	light Wino	light Higgsino
	$M_2 < \mu$	$\mu < M_2$
$\chi_1^0\chi_1^0$	$(\frac{m_Z}{\mu})^2$	$(\frac{m_Z}{\mu})^2$
$\chi_1^\pm\chi_1^0$	$(\frac{m_Z}{M_2})(\frac{m_Z}{\mu})$	$(\frac{m_Z}{\mu})$
$\chi_1^\pm\chi_1^\mp$	1	1
$\chi_1^0\chi_2^0$	$(\frac{m_Z}{\mu})^2$	$(\frac{m_Z}{\mu})$
$\chi_1^\pm\chi_2^0$	1	1
$\chi_2^0\chi_2^0$	$(\frac{m_Z}{\mu})^2$	$(\frac{m_Z}{M_2})^2$
$\chi_1^\pm\chi_3^0$		1

talk @ SUSY11 by S. Su

Nice coverage of direct EW ino production (mostly Bino LSP case)

light wino $M_1 < M_2 < \mu$



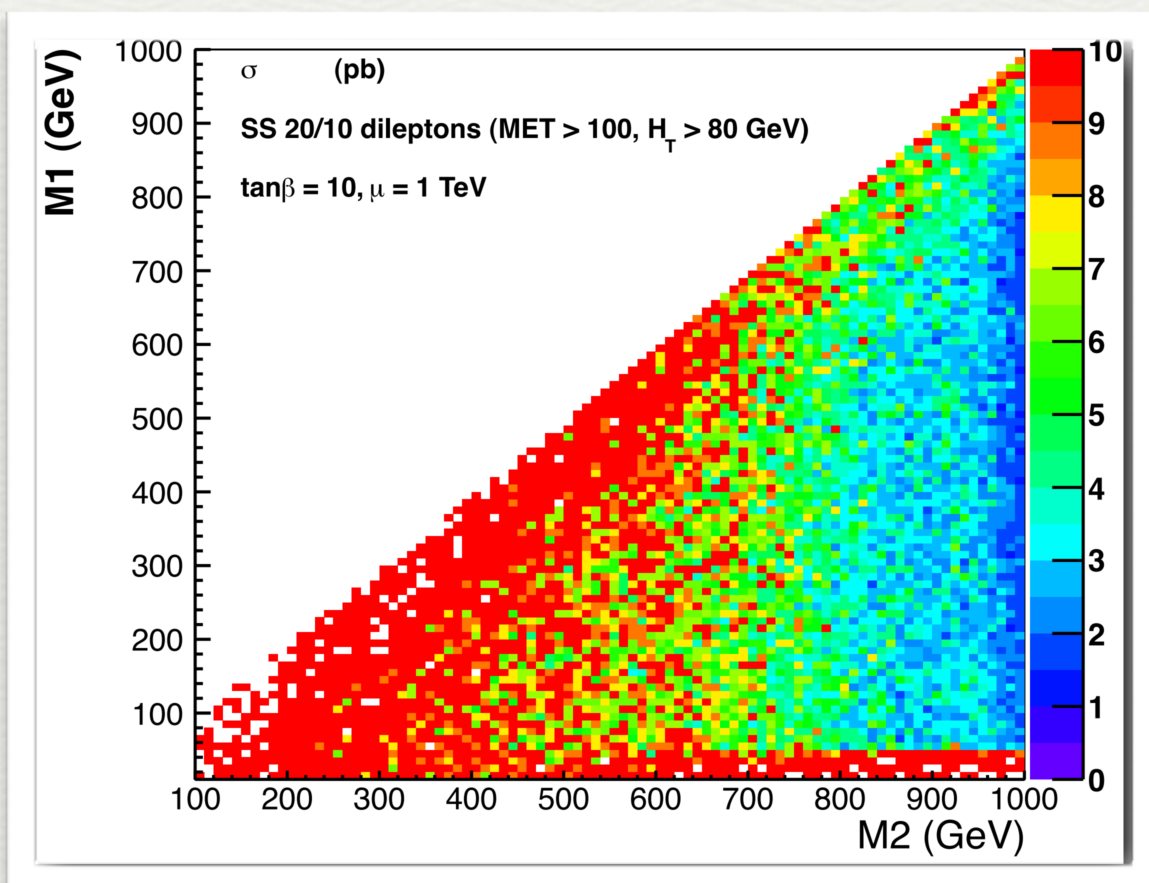
	light Wino	light Higgsino
	$M_2 < \mu$	$\mu < M_2$
$\chi_1^0\chi_1^0$	$(\frac{m_Z}{\mu})^2$	$(\frac{m_Z}{\mu})^2$
$\chi_1^\pm\chi_1^0$	$(\frac{m_Z}{M_2})(\frac{m_Z}{\mu})$	$(\frac{m_Z}{\mu})$
$\chi_1^\pm\chi_1^\mp$	1	1
$\chi_1^0\chi_2^0$	$(\frac{m_Z}{\mu})^2$	$(\frac{m_Z}{\mu})$
$\chi_1^\pm\chi_2^0$	1	1
$\chi_2^0\chi_2^0$	$(\frac{m_Z}{\mu})^2$	$(\frac{m_Z}{M_2})^2$
$\chi_1^\pm\chi_3^0$		1
$\chi_1^0\chi_3^0$		$(\frac{m_Z}{\mu})$
$\chi_2^0\chi_3^0$		1
$\chi_3^0\chi_3^0$		$(\frac{m_Z}{M_2})^2$

	light Wino	light Higgsino
	$M_2 < \mu$	$\mu < M_2$
$\chi_1^\pm \to \chi_1^0 W^\pm$	$(\frac{m_Z}{M_2})(\frac{m_Z}{\mu})$	$(\frac{m_Z}{\mu})$
$\chi^\pm \to \ell\tilde{\nu}_\ell, \tilde{\ell}\nu_\ell$	1	$(\frac{m_Z}{M_2})$
$\chi_2^0 \to \chi_1^0 Z$	$(\frac{m_Z}{\mu})^2$	$(\frac{m_Z}{\mu})$
$\chi_2^0 \to \chi_1^0 h$	$(\frac{m_Z}{\mu})$	1
$\chi_2^0 \to \ell\tilde{\ell}_L, \nu_\ell\tilde{\nu}_\ell$	1	$(\frac{m_Z}{\mu}), (\frac{m_Z}{M_2})$
$\chi_2^0 \to \ell\tilde{\ell}_R$	$(\frac{m_Z}{M_2})(\frac{m_Z}{\mu})$	$(\frac{m_Z}{\mu})$

Direct EW inos prod’

- S. Su, T. Han, S. Padhi, to appear soon

study constraints on EW ino direct production from CMS SS dilept’



No reach with 0.98 fb-1, need more data

Best sensitivity with low HT requirements in that analysis

Different signatures without leaving the MSSM

There's the gravitino...

$$m_{3/2} = \frac{F}{\sqrt{3}M_{Pl}} \qquad m_{SUSY} \propto \frac{F}{\Lambda_M}$$

$$\Gamma(NLSP \to SM + \tilde{G}) \propto \frac{m_{NLSP}^5}{8\pi F^2}$$

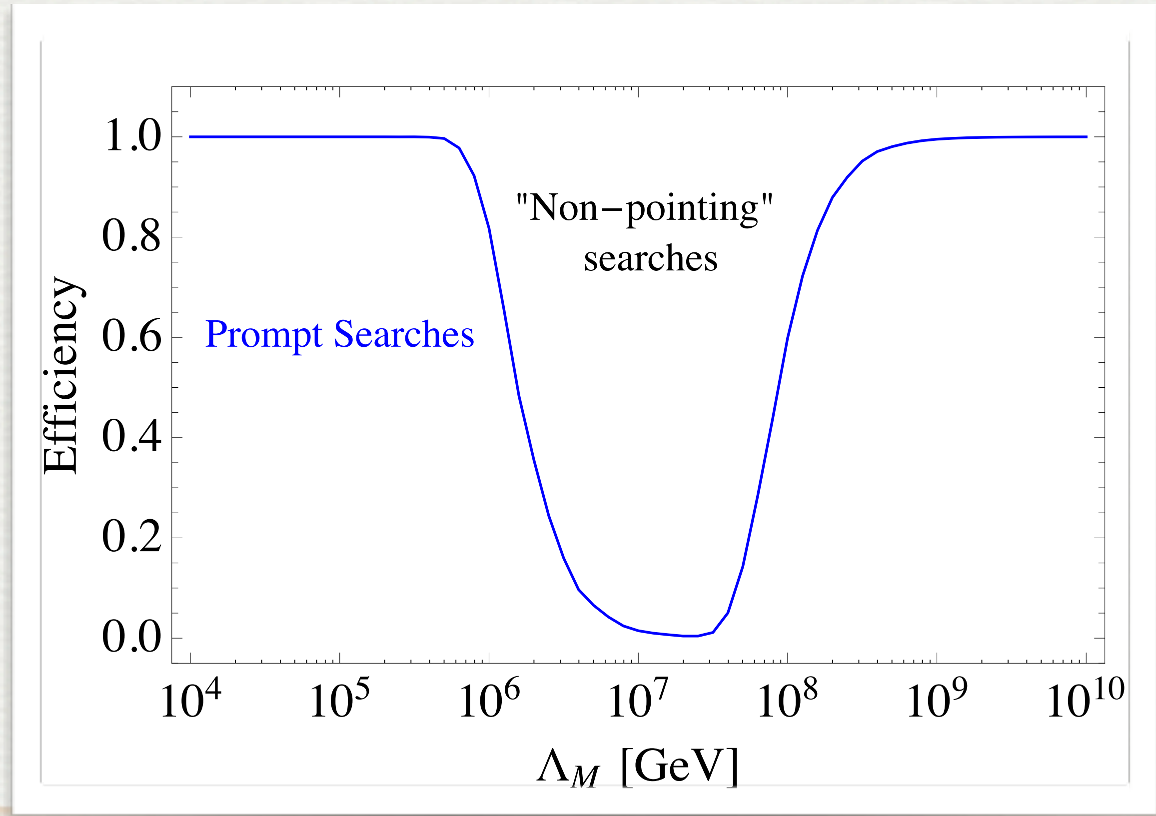
It can easily span very different masses and very different lifetimes depending on where/how SUSY is broken...

There's the gravitino...

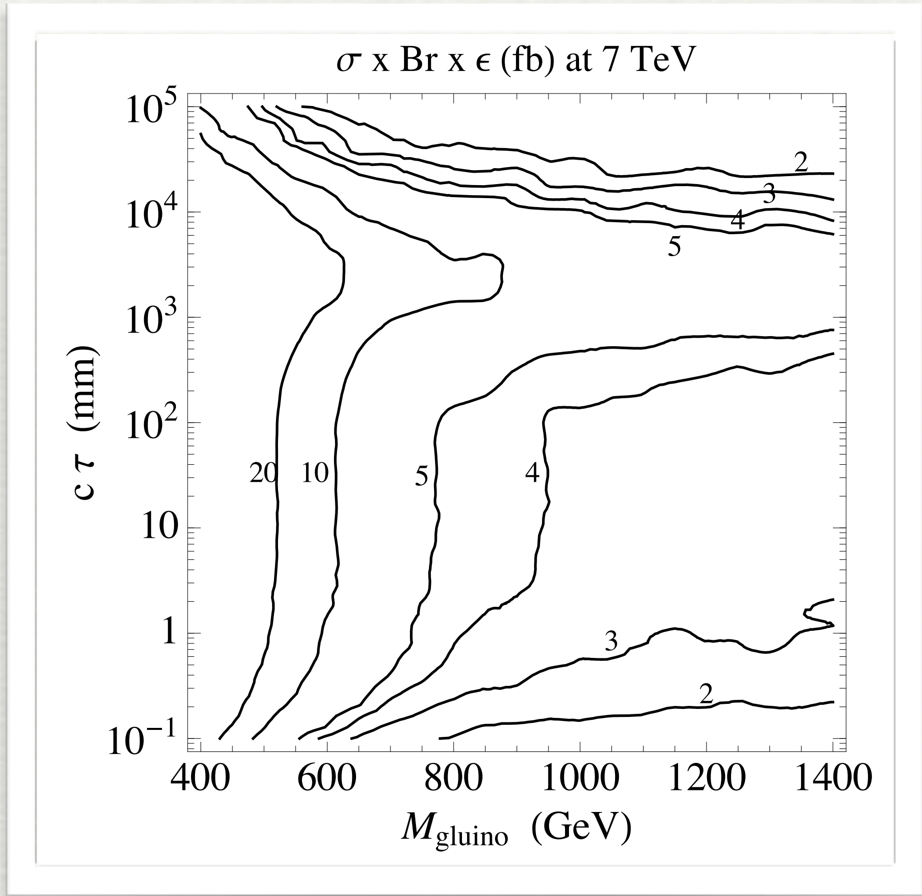
... it can be light (not a big deal, still MET+X), and make the NLSP long lived!!

A window of ~2 orders of magnitude for SUSY mediation scale with reduced sensitivity (about a factor of 10) w.r.t. standard searches

- Neutral NLSP: non-pointing photons (classic), but also non-pointing $Z^{(*)}$ or even Higgs

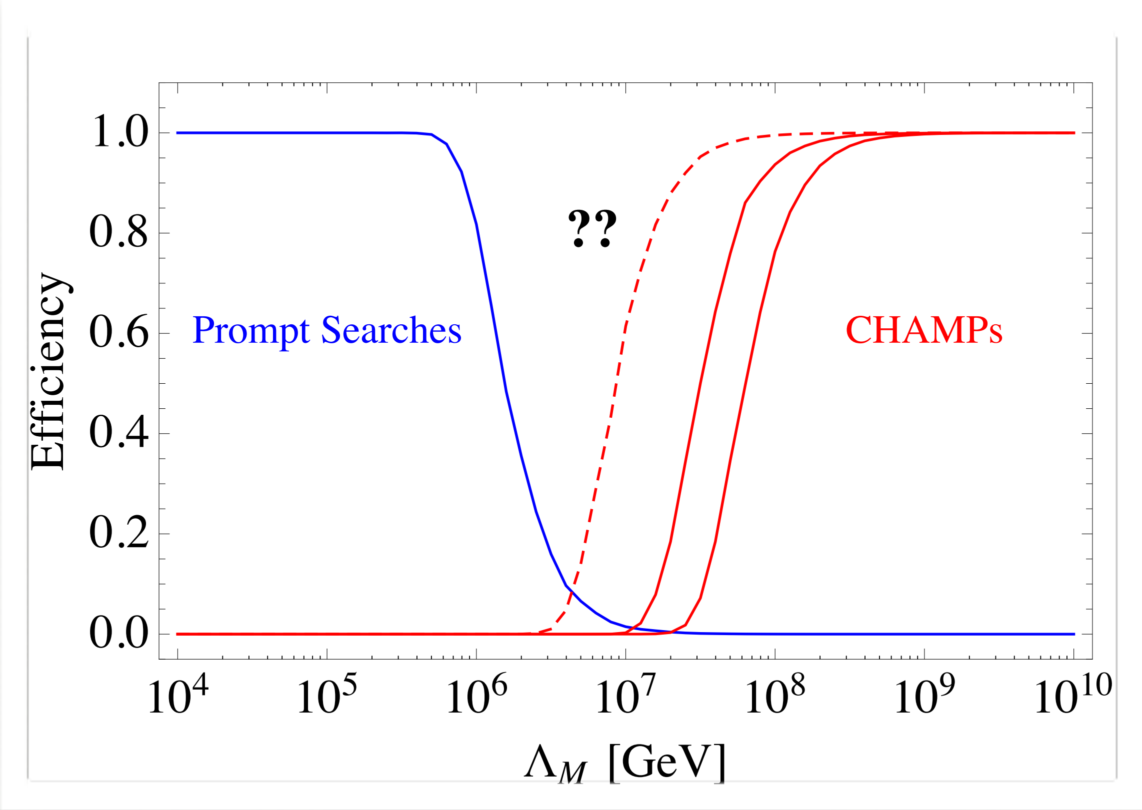


- Neutral NLSP: Meade et al. explored LHC reach for NLSP→ Z gravitino



Meade et al. 1006.4575

- Charged/colored NLSP: if travel long enough it gets caught in CHAMPs searches.
- Charged final state can be pretty much anything (from leptons to jets to even tops)
- Searches??



"Compressed" spectra?

- Dealing with squeezings is very relevant after discovery to be able to access the whole susy spectrum
- Difficult to have scenarios where exp' reach is penalized across multiple searches by just a squeezed spectrum (but it is a logical possibility):
    - Different masses → different radiative corrections: difficult to keep whole spectrum together separated by small splittings
        - Running from high scale tend to open up the SUSY spectrum → low scale SUSY breaking required
        - Generically more fine-tuned
- Using hard ISR to overcome energy thresholds by recoiling against a hard jet (need statistics: xsec * ~0.1 from α_s * pdf suppression due to larger H_T)

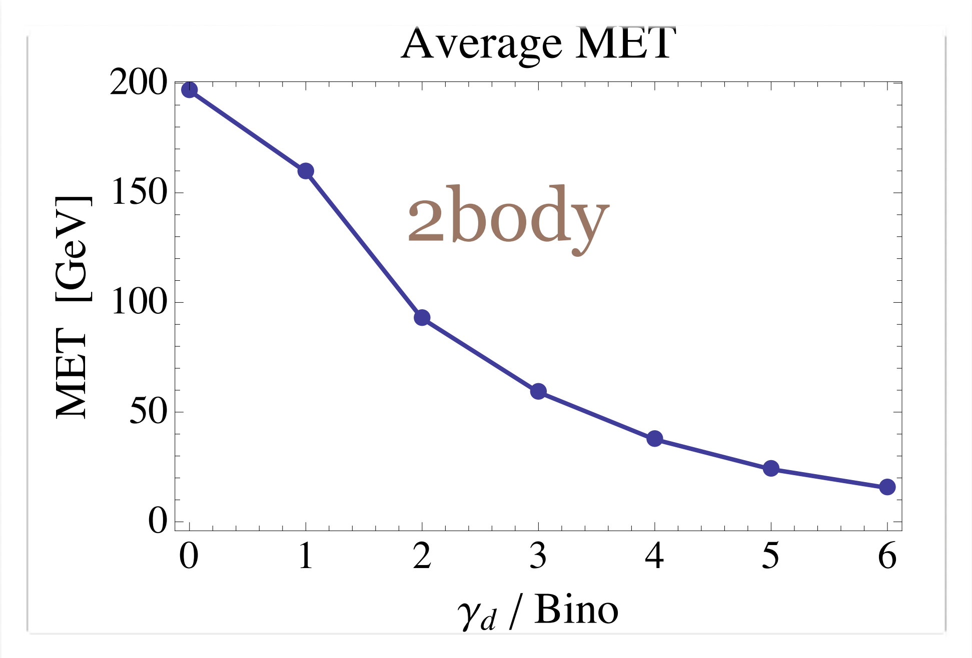
MC: need to get that jet from the matrix element and not from the shower (and matched sample depending on the cuts)

SUSY signatures beyond the MSSM

Reducing the missing ET (with RP conserv)

- Reducing the missing ET below the exp' resolution is not easily done and not fully explored in the literature (various theorists are working on it, stay tuned)

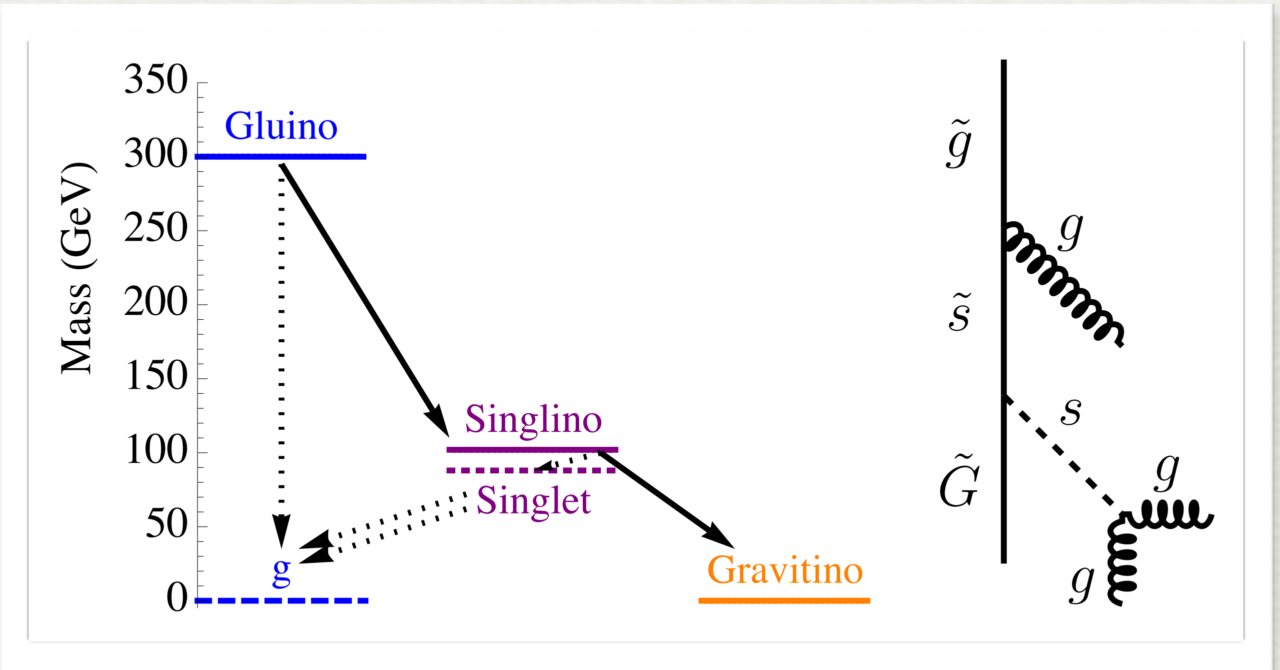
Increasing the length of the cascade with new (non-MSSM states) tend to need many stages (less stages if multibody decays at each stage)



plot by J.Ruderman

"Stealth": easier to use phase space

Having a small splitting at the NLSP stage + very light LSP (gravitino...)



Fan Reece Ruderman 1105.5135

“Stealth” SUSY

- Simplest model: add a singlet to the MSSM (a.k.a. the NMSSM). Small splitting can be achieved naturally
- not “hiding SUSY”, just making it discoverable in non-MET analyses
- Generic feature: pair of multibody resonances (since MET is small)
- Some signatures already looked for: e.g. 3-jet “resonances”
- Other signatures proposed, e.g. “resonances” in 1jet +2photons. There are more cases to explore (in the paper just a few examples)

Outlook

- We passed the divide between constraining only 1st-2nd gen' squarks & gluinos initiated cascades vs. looking at direct production of the rest 3rd gen' squarks and electroweak "inos"
- Strong limits on squarks and gluinos are currently "trouble" only for (high-scale) flavor-universal scenarios
- Partial list of things to start looking for (while keep pushing gluino and squark bounds)
  - light stops and sbottoms (start already being constrained)
  - weak inos
  - Low MET scenarios, RPV
  - Long lived NLSP (neutral and charged)
  - Compressed spectra
  - ...